The Geophysics Contributions from the QJEGH, 1967 - 2015

ABSTRACT

This paper reviews the geophysics contributions of the QJEGH (and forerunner QJEG) over the last 50 years in support of engineering geology, hydrogeology and ground engineering. It includes a brief history of some world and national influences on the ascent of geophysics over this time. The fundamental objectives behind geophysical surveying and monitoring are recapped before presenting contributions, across a range of geophysical methods, within a framework of applications, originally devised by the Geological Society Engineering Group Working Party for Engineering Geophysics in 1988. Three quarters of the papers reviewed focused on UK geology. Seismic, electrical resistivity and thermal methods accounted for 60% of the contributions, with magnetic, gravity and seismicity accounting for a further 24%. Some contributions are highlighted in each of the applications sections; these were considered exemplars of good practice, of good data, or considered by the reviewer to be innovative (at the time). Tables classifying around 140 papers into geophysical themes will enable practitioners to utilise the Geological Society Online Lyell Collection to review appropriate geological and hydrogeological contexts for successful engineering geophysical applications in support of future engineering.

1. Review Structure

The Quarterly Journal of Engineering Geology (QJEG) was established to support the Engineering Group of the Geological Society, with its first publication in 1967. In 2000, the name of the Journal was changed to the Quarterly Journal of Engineering Geology and Hydrogeology (QJEGH), providing more explicit recognition of the significance of hydrogeology to ground engineering. This paper forms part of a series celebrating the journal's contribution across a range of relevant subject areas during its first 50 years of publication. The series commenced with an overview paper that set out the origins, history and status of the journal (Winter & Bromhead, 2016) before taking a very brief look at the future. Covered here are the geophysical contributions made by the journal from 1967 to 2015, which can be used in conjunction with other papers dealing with connected topics, such as the reviews on: terrain evaluation, mapping and geological models by Griffiths (2017), aggregates and earthworks and geomaterials by Cassar & Standing (2017).

Ascent of Geophysics over the last Half-Century

Much of today's geophysics practice, has in part, been shaped by significant global events during the period covered by this review. Many geophysical techniques ascended to address the survey and monitoring demands in support of UK and overseas development. In the 1960s, during the Decade of Development, the Dept. of Technical Co-operation supported much exploration geophysical activity to assist the economic development in Kenya, Uganda and Nigeria after their independence from colonial rule. Regional mapping and exploration over depositional basins, fold belts, intrusions and faulted structures also aided surveys for coal and hydrocarbons, ground water and metalliferous mineral resources. Early geophysical instruments were developed for rapid reconnaissance over large areas, notably employing magnetic, gravity, electrical and electromagnetic methods. QJEGH features these same basic methods but often in an alternative form refined for engineering geophysical applications. For example, electrical resistivity was a preferred method for mapping superficial soils in UK river catchments and overseas desert wadi in the ***Geological Applications*** (section below), and also in ***Resource Applications*** for aggregates assessment and mapping aquifer subcrop.

A rapidly growing world demand for hydrocarbon products led to the formation of many national oil companies around 1970. Oil prices quadrupled around the 1973 Arab-Israeli War, sparking increased exploration for new reserves in Western Europe in the early 1970s, and later in the US and Arabia. Exploiting the digital processing revolution of the 1960s-1970s, seismic reflection systems were able to image large onshore and offshore reservoir structures (US Oil & Gas Energy Information Administration 1993). Meanwhile, Dr. Beeching's 'Major Railway Trunk Routes' were valiantly resisting the UK's rail decline during the largest expansion of our motorway network in history. Over 600 miles were built during the 1960s, including key N-S links along the current M1 and M6; nearly 1000 miles were built during the 1970s, developing the E-W links such as the M4, M6 (-M1 link), M62 and the M5; while during the 1980s a further 300 miles contributed to the city circulars, such as the M25, M42 and M60 around London, Birmingham and Manchester. Many large scale earth movements required detailed knowledge of shallow engineering geology, and geophysical methods specialised for geotechnical property characterisation, identification of aggregrates and bedrock profiling in the upper 50 to 100 m were in demand. Reflection and refraction seismic surveys with higher frequency sources than their hydrocarbon counterparts were used in ***Geological Applications*** to map superficial sequences in glaciolacustrine, fluviatile and coastal settings. S-wave refraction was especially successful for characterising ground stiffness, while P-wave surveys were used for shallow coal excavatability assessments in ***Engineering Applications***.

Metropolitan expansion during the 1980s and 1990s placed increased pressure on the reuse of contaminated and derelict ground around our urban centres. Building on the UK's geological mapping programme (that existed at that time), the Dept. of the Environment commissioned a series of 'planning and development' studies focusing particularly on 'industrial' cities that had suffered decline. Early studies focused on engineering geological influences on land use, such as in Coventry, the Black Country, Morpeth, Nottingham (Charsley et al. 1990), Garforth, Stoke on Trent (Wilson et al. 1992), Leeds; later studies included an additional user guide for dealing with the ground conditions, e.g. Wigan and Bradford (Waters et al. 1996)[1]. Improved microgravity and magnetic gradiometer instruments were developed to characterise legacies of anthropogenic dereliction, where the ***Hazardous Ground Applications*** include some cases of their use for abandoned mineshafts detection.

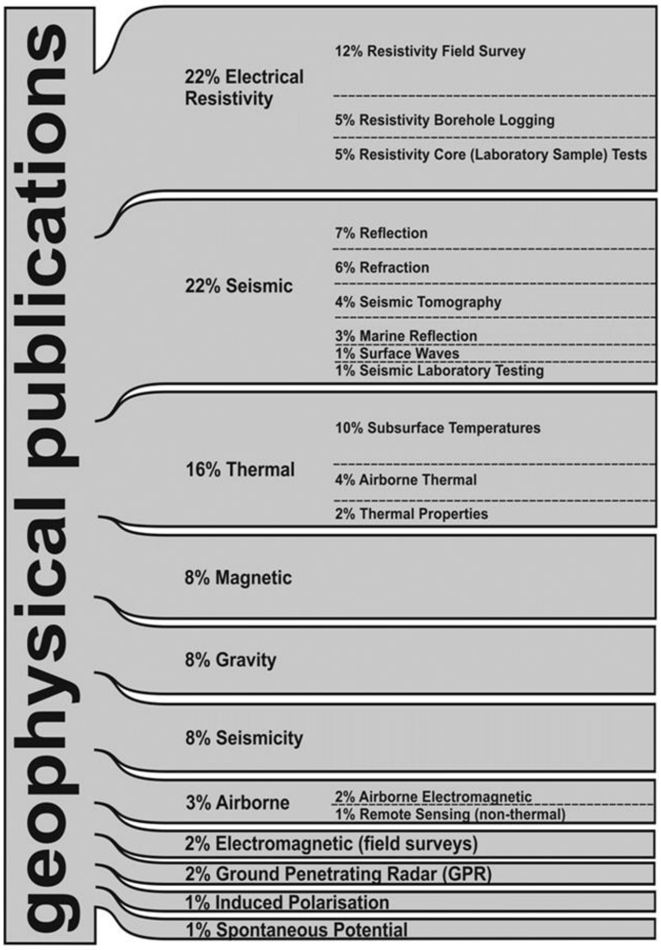
Enforcement of the evolving Environmental Protection Act 1990 (updated as recently as 2008) required new methods for identifying and locating the physical and chemical legacies of former land use, and also, for monitoring the subsequent remediation of affected ground. Identification of aqueous and non-aqueous contaminants, hydrogeological pathways and vulnerable receptors drove the need for volumetric geophysical imaging techniques deployed from both the surface and downhole. Notable successes in the ***Resource Applications*** include location and monitoring of saline intrusion into the NW England Permo-Trias aquifer, and downhole resistivity tomography to isolate permeable, fractured intervals during packer and tracer tests.

The growth of the innovation and service sectors drove a major shift in UK work patterns from the 1990s and into the 'noughties' (2000s), certainly until 2008. Many city skylines grew as office spaces of smaller footprints replaced former factories in the new urban workspace, which has since become increasingly congested. Urban populations continue to swell, and a smart, sustainable subsurface is recognised as critical to our energy efficient and liveable cities of the future (Swinney & Thomas 2015). The sensor systems specialised for today's shallow, high resolution utility surveys are the refined descendants of their GPR and electromagnetic relatives. Indeed, this review extends the original classification devised by McDowell *et al.* (2002) with an ***Infrastructure Applications*** section, which includes early use of GPR to assess the condition of highway sub-base. This section also focuses on recent work to assess the behaviour of the subsurface as a platform for energy efficient heat storage and transfer in our modern cities.

This review returned around 140 original papers, which were classed into the geophysical themes in the proportions shown in Text Box 1 (i.e. the selected class was either the only or the most significant theme). Notably,

[1] These references are not exhaustive.

seismic and electrical surveying methods were reported most. This related to the versatility, ready scalability and potential for fairly rapid coverage (aerial and depth) of fundamental ground information on mechanical properties or the distribution of moisture, reflecting associated litho-stratigraphy. There was also significant work regarding subsurface temperature measurement, which related to the potential for the ground to source, store and exchange heat. These three geophysical categories accounted for 60% of the papers reviewed, with magnetic, gravity and seismicity accounting for a further 24%. Magnetic methods mainly related to detecting field disturbances due to the presence of mafic intrusions or anthropogenic inclusions like shaft linings, infill or utilities. Gravity methods related to density contrasts from buried valleys or voiding and related subsidence, and seismicity to natural earthquakes or events related to mining. While other methods were encountered to a lesser degree, (see Text Box 1), this review has also attempted to capture these contributions, especially where they were unique.



Text Box 1: Geophysical search themes and their relative occurrence in this literature review.

<u>Geophysics Classification for Ground Engineering and Hydrogeological Applications</u>

The theoretical and practical background to geophysics has been extensively reviewed in several works such as Telford et al. (1976) and Parasnis (1979), with groundwater, engineering and environmental investigations covered in some detail by Kelly & Mareš (1993) and Reynolds (1997). While there are various nuances across these works, the three fundamental objectives underlying geophysical surveys for engineering geological and hydrogeological applications include:

i. ***Mapping*** geological or engineering geological distributions for ground classification or characterisation; where to many, 'mapping' implies lateral outcrop, whereas 'characterisation' often includes more detailed information regarding property and spatial variability, including information about subcrop, or property-depth logs, sections or 3D ground models;

ii. ***Detecting*** anomalies associated with poor ground conditions, natural or anthropogenic hazards, or buried objects (or obstructions); where 'detection' and 'location' are often inter-changeable; and

iii. ***Monitoring*** processes leading to property changes; by repeated surveying over a constant volume, of the spatial and temporal evolution of geophysical properties; characterising underlying processes, including hydrological (groundwater movement), stress (earthquakes, fault movement) or load related (consolidation) processes, where geotechnical property changes are detected via measureable geophysical proxies.

Working tables in Appendix A summarise contributions across these geophysical objectives to UK and international engineering projects, focusing particularly on UK geology and engineering formations. These tables include all papers recovered in the review and are intended to provide a geophysical background context relevant for current engineering practice. However, to understand the geophysical contribution to engineering over the history of the QJEGH, this review is framed broadly within the 'engineering applications' of McDowell et al. (2002), outlined in Table 1. This framework also embodies the structure of the Geological Society Engineering Group Working Party for Engineering Geophysics (1988), which outlines the ground information provided by common geophysical methods and gives guidance on their use for engineering applications, and for which, this review is no substitute. The Geological Society Engineering Geology Special Publication No. 12, 'Modern Geophysics in Engineering Geology' edited by McCann et al. (1997) is also recommended as a source of information regarding standards and practice for geophysics in laboratory studies, site investigation and rock mass assessment. This current review also captures papers from other themed issues, including the 'Application of Geophysics in Shallow Sedimentary Environments' (Cassidy 2005), 'Hydrogeology in Heat Engineering' (Buss 2009) and the opening by Chaplow (1996) to the workshop on the Sellafield Ground Model, shown in Figure 1, which incorporated one of the UK's largest geophysical datasets, including 1950 km of offshore and onshore seismic reflection, 8500 km of airborne magnetic and gravity profiles, and around 20 km of wireline data including electrical, sonic, caliper and nuclear logs throughout 20 deep boreholes.

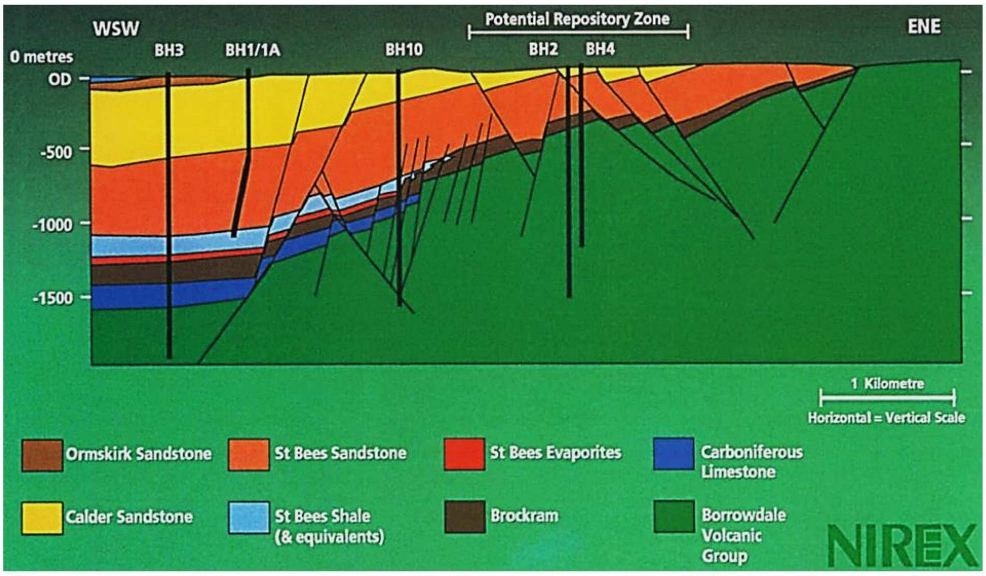


Fig. 1. Sellafield Ground Model; schematic geological WSW-ENE cross section, from Chaplow (1996)

Table 1. Ground engineering applications, showing common objectives and activities of the geophysical methods (or themes) searched as part of this review.

Problem		Ground Investigation Activities		
Broad Class	**Specific Application**	**Site Investigation Objective**	**Common Geophysical Methods Used**	
Geological	Stratigraphical	1. Drift / Depth to bedrock	Seismic: Electrical:	Reflection; Refraction Resistivity; Electromagnetic (EM)
		2. Litho-facies differentiation (esp. sand / clay)	Seismic: Electrical: Borehole: (incl. core logs)	Reflection; Resistivity; Gamma; Acoustic; Electrical Logs:- incl. Induction; Resistivity
	Erosional	Buried Valleys and Channels	Seismic: Electrical: Gravity:	Reflection; Refraction Resistivity; EM Gravity surveying
	Weathering	Soil profile; Buried karst	Seismic: Gravity: Electrical:	Refraction Gravity suveying Resistivity; GPR; EM
	Structural	Faults; Folds; Igneous intrusions Joints (e.g. major sets as opposed to rock mass-fracture charact^n)	Gravity: Magnetic: Seismic: Electrical:	Gravity surveying Magnetic field/gradient surveying Reflection; Tomography Resistivity; EM; GPR (shallow)
	Geomorphological Mapping	Geomorphological; engineering geological mapping, differentiating fine vs coarse soils; or wet vs dry surface features	Airborne:	Aerial Photographs; Satellite InSAR Thermal IR; EM; Radiometric
Resources	Water	1. Aquifer aerial mapping and subsurface location	Seismic: Electrical: Airborne: (near surface)	Reflection; Refraction Resistivity; EM Thermal IR; Radiometric; EM
		2. Aquifer/hydrogeological property characterisation (incl. porosity, permeability, fracture conductivity or transmissivity..)	Seismic: Electrical: Borehole: (incl. core logs)	Reflection; BH Tomography Resistivity; Gamma; Neutron Density; Acoustic; Electrical Logs:- incl. Induction; Resistivity
		3. Heat Energy: 'High-enthalpy' low-temperature hot water injection, circulation, abstraction; heated water for electricity generation	Borehole: (incl. core logs) Thermal:	Gamma; Neutron Density; Acoustic; Electrical Logs:- incl. Induction; Resistivity Regional and local (BH) temperature field monitoring
	Geo-environmental (incl. Contamination; Pollution..)	1. Saline intrusion; saline-freshwater delineation	Seismic: Electrical: Borehole: (incl. core logs)	Reflection; BH Tomography Resistivity; Gamma; Neutron Density; Acoustic; Electrical Logs:- incl. Induction; Resistivity
		2. Contamination plumes, incl. landfill gas; leachate; NAPL / DNAPL; also acid groundwater		
	Sand & Gravel	1. Glacial, river terrace deposits (and occasional coastal beaches) over bedrock	Electrical:	Resistivity; GPR; EM;
		2. Coastal and estuarine sand and gravel	Seismic:	Reflection (incl. towed arrays); Sonar (echo / bathymetry sounders and side-scanning)
Engineering	Geomechanical / Deformation behaviour	1. Elastic moduli; Poisson's Ratio; Stiffness (small strain)	Seismic: Borehole: (incl. core logs)	Refraction; Reflection; BH Tomography; Surface Waves Neutron Density; Acoustic Logs
		2. Mining collapse; shale gas fracking	Seismic:	Seismicity Monitoring
	Geotechnical evaluations	Fracture characterisation / Rock mass quality designation; penetration (resistance) and piling	Seismic: Borehole: (incl. core logs) Thermal:	Refraction; Reflection; BH Tomography; Neutron Density; Acoustic Logs; also Electrical Logs:- incl. Induction; Resistivity Thermal Conductivity Probe
	Excavation evaluation	Rippability; Diggability; Trenchability	Seismic:	Refraction; BH tomography
	Soil Chemistry	Corrosivity: Sulphates (concrete); pH (metal pipes); Soil conductivity-electrical earthing	Electrical:	Resistivity; EM

Table 1. Ground engineering applications, cont.

Problem		Ground Investigation Activities		
Broad Class	**Specific Application**	**Site Investigation Objective**	**Common Geophysical Methods Used**	
Hazardous Ground	Voids	1. Natural voids; sinkholes; dolines; dissolution cavities	Gravity: Seismic: Electrical: Airborne:	Gravity / micro-gravity surveying Refraction Resistivity; EM; GPR (shallow) Thermal IR; Radiometric (e.g. Lmst)
		2. Shafts; mineworkings; tunnels	Gravity: Magnetic: Seismic: Electrical: Airborne:	Gravity / micro-gravity surveying Magnetic field/gradient surveying Refraction; Seismicity Monitoring Resistivity; EM; GPR (shallow) Thermal IR; Radiometric (e.g. Lmst)
	Weak / Disturbed ground	Differential settlement; landslides; subsidence	Seismic: Electrical: Airborne:	Refraction; Surface Waves Resistivity; EM; GPR (shallow) Satellite InSAR
	Volcanic Hazards	Volcanic crators; fumarolic emissions; hot spring emissions (geysers); subsurface lava pipes; lava flows	Gravity: Magnetic: Seismic: Airborne:	Gravity / micro-gravity surveying Magnetic field/gradient surveying Seismicity Monitoring Thermal IR; Satellite InSAR
Infrastructure	Pavement / foundations evaluations	1. Roads; Rail - ballasted track	Seismic: Electrical: Thermal:	Surface Waves; Acoustic echo test Resistivity; GPR Infra-Red scanning (fouled-saturated ballast)
		2. Buried walls; foundations (incl. archaelogical remains)	Seismic: Magnetic: Electrical:	Refraction Magnetic field/gradient surveying Resistivity (often shallow profiling); GPR; EM occas.
	Engineered earthworks	Embankments, cuttings, dams	Seismic: Electrical: Thermal:	Shallow Refraction; Surface Waves Resistivity (time lapse monitoring); EM; GPR Infra-Red scanning (seeps)
	Buried utilities	Pipes and cables; location; condition and performance; incl. soil-heat exchange	Electrical: Magnetic: Thermal:	Mainly GPR; also shallow EM Mag. Field from cable currents Heating in high resistance nodes
	Ground Source Heat Pumps	3. Heat Energy: Low-enthalpy heat storage, cooling, energy harvesting, retrieval; 'High-enthalpy' low-temperature hot water injection, circulation, abstraction; heated water for electricity generation; Open loop / Closed Loop GSHP	Borehole: (incl. core logs) Thermal:	Gamma; Neutron Density; Acoustic; Electrical Logs:- incl. Induction; Resistivity Regional and local (BH) temperature field monitoring

2. QJEGH Geophysical Contributions to Engineering Applications

<u>QJEGH Geophysics Review at a Glance</u>

Table 2 shows the world regions represented by the papers, with a more detailed breakdown of the contribution (75%) to UK bedrock and superficial engineering geology. Figure 2 shows the broad regional distribution of engineering applications and associated geophysical support, which is influenced by the geography of the UK bedrock and superficial engineering geological formations. Text Box 2 summarises the broad UK distribution of engineering applications, geological formations and the geophysical support, including more commonly encountered methods such as:

i. electrical resistivity surveys supporting bedrock aquifer and groundwater assessments in the South-East, North-West, East-Midlands and West-Midlands,

ii. seismic surveys supporting geological evaluation of coal measures bedrock especially in Yorkshire-Humberside and the North-East, and of alluvial/glacio-lacustrine and coastal/estuary superficial litho-stratigraphy in Wales and East-Anglia,

iii. subsurface thermal monitoring to support heat storage and supply in London and the South-East, and,

iv. micro-seismic monitoring of collapsing coal mines in Scotland and the East-Midlands, limestone mines in the West-Midlands and earthquake risk in Wales, the North-West, South-East and South-West.

Table 2. Relative significance of QJEGH 1967-2015 geophysical contributions to international and UK engineering geology.

World Regional Representation			
UK	75%		
Europe	6%	Arabia	6%
Australasia	5%	Africa	4%
Scandanavia	2%	Americas	2%

UK Papers:- Geophysics Contributions to Bedrock Engineering				and to Superficial Engineering	
Aquifer / Heat Storage	40%	Chalk	17%	Glaciofluvial / Terrace	29%
		Permo-Trias Sst	13%		
		Carboniferous Lmst	7%		
		Jurassic Lmst	2%		
		Lower Greensand	1%		
Mudstones	18%	Mercia Mudst	2%	Alluvium / Glaciolacustrine	23%
		Mesozoic Mudst	9%		
		London Clay	7%		
Coal	18%	Coal Measures	16%	Tidal / Estuary / Coastal	23%
		Millstone Grit	2%		
Basement	10%	Lower Palaeozoic	5%	Till	17%
		Crystalline / Pre-Cambrian	5%		
Aggregate / Contamination	8%	Tertiary Crags / Sand& Gravel	8%	Engineered Ground	4%
Subsidence	5%	Evaporites / Salt	5%	Aeolian / Loess	4%

Fig. 2. Geographic representation of the papers focused on UK engineering geology.
(Legend arranged in descending representation of regional UK coverage).

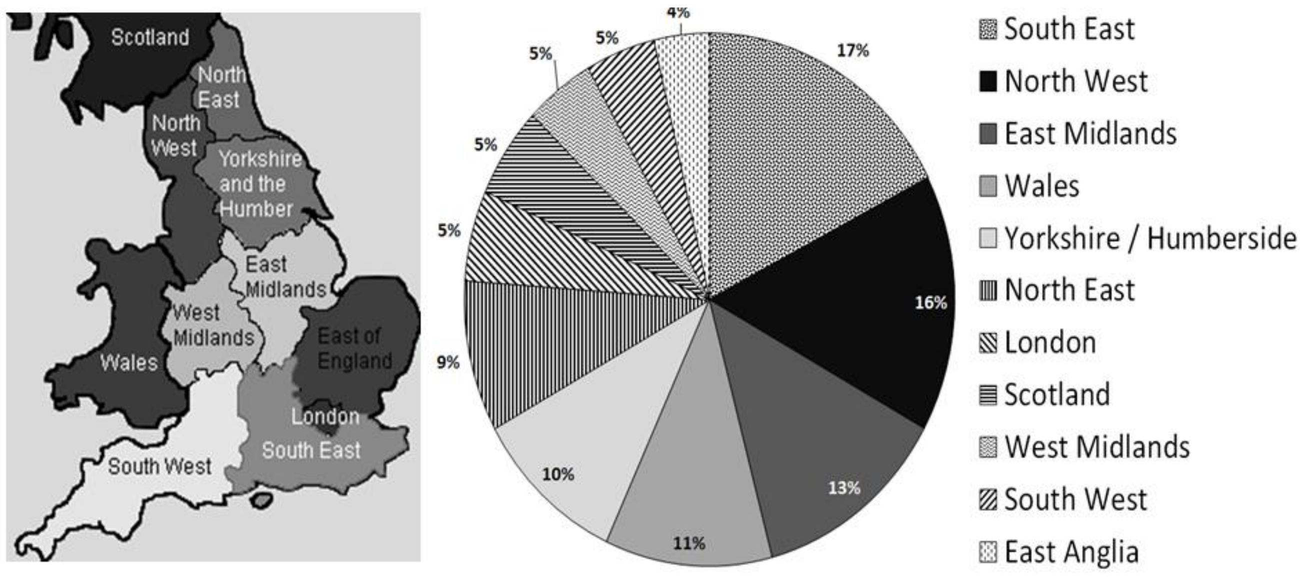


Table 1 represents a refinement of the original classification of engineering geophysical methods devised for British Standard BS 5930:1981, where it formed four primary applications: i. Geological investigation, ii. Assessment of materials and water resources, iii. Determination of engineering parameters, and iv. Detection of voids and buried artifacts. The report by the Geological Society Engineering Group Working Party on Engineering Geophysics (1988) and the CIRIA Report C562, ‘Geophysics in engineering investigations’ by McDowell et al. (2002) were framed using this structure, which is still used in ‘Section 5 Geophysical field investigations’ of BS 5930:2015. It isn’t possible to mention all the QJEGH geophysical contributions over this last 50 years, but using this well-tested framework, the remainder of this review highlights some exemplars of innovations, good practice and good data of interest to engineering practitioners.

South East: **Bedrock:** Aquifer (GW quality) [Resistivity]; Mudstone Stratigraphy [Seismic/Resistivity]; Heat Storage and Supply [Thermal]; Microseismic Monitoring;

North West: **Bedrock:** Aquifer (GW quality) [Resistivity]; Coal Measures [Seismic/Resistivity]; Fracking [Seismicity]; Salt-Subsidence [Gravity];
Superficial: Estuarine & Coastal Sediments [Seismic]

East Midlands: **Bedrock:** Aquifer [Resistivity]; Mudstone Stratigraphy [Seismic/Resistivity]; Coal Measures [Seismic/Resistivity]; Mine Shafts-Collapse [Thermal/Seismicity];
Superficial: Terrace (Aggregates) [Seismic];

Wales: **Bedrock:** Coal Measures [Seismic/Resistivity]; Basement [Seismicity]; Microseismic Monitoring;
Superficial: Alluvium/Glaciolacustrine/Till (Poor foundation conditions)[Seismic];Engineered Ground-Voids [GPR]; Tidal Beach & Coastal Sediments [Seismic]

York/Humber: **Bedrock:** Coal Measures [Seismic/Resistivity]; Mine-Shafts [Airborne Thermal, Gravity/Magnetic]; Evaporites Dissolution-Subsidence [Gravity/Seismic];

North East: **Bedrock:** Coal Measures [Seismic/Resistivity]; Crystalline/Basement Hot-Dry Rock [Thermal]; Urban Heat Island [Thermal];

London: **Bedrock:** Aquifer (GW quality) [Resistivity]; Tertiary Stratigraphy [Seismic]; Heat Storage and Supply [Thermal];
Superficial: Terrace (Aggregates) [Seismic];

Scotland: **Bedrock:** Coal Measures [Seismic/Resistivity]; Mine Water Heat Storage and Supply [Thermal]; Crystalline/Basement GW springs [Thermal];

West Midlands: **Bedrock:** Aquifer (GW quality) [Resistivity]; Mine-Collapse [Seismicity];

South West: **Bedrock:** Microseismic Monitoring;

East Anglia: **Superficial:** Tertiary (Aggregates) [Seismic]; Estuarine & Coastal Sediments [Marine Seismic]

Text Box 2: Summary of the regional distribution of engineering applications, formations and the geophysical support within the UK.

Hazardous Ground Applications

This relates to prevailing conditions causing poor or weak ground, or potential instabilities such as subsidence, settlement or heave due to anthropogenic hazards, such as mine workings and shafts, natural hazards such as sinkholes, dissolution features (voids, cavities), landslides, or induced by earthquakes or volcanoes. This section was placed first to highlight the *Magnetic* contributions by Taylor (1968), who while searching for shallow mine workings in the Coal Measures in Yorkshire, reminded us of the engineer's ever present scepticism of geophysics before conceding that '..the proton magnetometer had been used with some degree of success in shaft location'. Taylor (1968) also conceded that, '.. a resistivity survey did indicate the strike direction of the rocks and two major anomalies proved to be 'bell-pits'. [Gunn *et al.* (2008) also used field magnetic gradiometer surveys to corroborate the presence of shafts located using aerial infrared.]

Gravity contributions relate to dissolution features, such as determining the location of a funnel-shaped doline in glacial sands and gravels in Ripon from a -70 ugals anomaly on a microgravity survey by Patterson et al. (1995). Later trenching confirmed the top to be < 2m deep at 16 m across, narrowing to an underlying pipe, 4 m wide infilled with clay, silty sands and gavels. Branston & Styles (2003) attributed a -30 ugal gravity anomaly change in Northwich to subsidence associated with shallow crown-hole development around 3 m deep caused by underlying salt dissolution at around 23 m.

Seismicity contributions relate either to earthquake ground shaking, fault rupture and ground deformation or to mining collapse. This method accounts for much of the overseas studies (Table 2), such as the compilation of a regional Arabian seismicity map by Ambraseys (1978), where relatively late urban development resulted in little anecdotal or instrumental evidence. Similarly, Husain-Malkani et al. (1995) developed a seismo-tectonic model and iso-seismal intensity maps for Jordanian seismicity, from which Husain-Malkani & Fahmi (1996) produced ground acceleration-attenuation curves for seismic hazard risk and building-design around Sinai. Xu et al. (2013) used weighted indices including distance from and along the fault zone, intensity and peak ground acceleration in an earthquake-induced landslide susceptibility GIS to produce damage forecasts from future ruptures. Work in the UK includes use of portable (single/3-component) microseismic networks for seismic risk assessments: e.g. by Aspinall (1990) who characterised the depths and fault rupture mechanisms of local, low magnitude ($M_L<3$) seismicity about Hinckley Point, Dungeness, Wylfa and Trawsfynydd nuclear power stations. Interestingly, although Skipp (1988) found little evidence of risk to Hinckley Point from Tertiary relaxation of the Watchet-Colthrestone-Hatch thrustfault in Somerset, planning application for the development of a pressurised water reactor was rejected as uneconomical in the 1990s.

UK mining-induced seismicity has been successfully monitored using both strong motion and microseismic networks. After simulating roof fall (hydraulic forcing) and collapse (weight drops) in the Castlefields Silurian Limestone mine, Miller at al. (1989) concluded that microseismic networks are most sensitive to the impact of fallen material on floors of open and flooded mines. Bishop et al. (1993) recorded hypocentre swarms on microseismic networks in Nottinghamshire that correlated spatially and temporally with the long wall advance in the Thoresby colliery around 700 m deep. Using the BGS strong motion network, Redmayne et al. (1998) suggested local ground motion amplification as a possible cause of relatively large magnitude (M_L>3) seismicity damaging Roslyn Chapel, which they attributed to stress redistribution from the Bliston Glen colliery. Finally, with fervent interest in UK fracking, Westaway & Younger (2014) incorporated seismic radiation theory into algorithms for predicting fracking-induced peak ground velocities (PGV) based on earthquake magnitude and epicentral distance. These algorithms are captured in a very informative summary diagram showing the potential PGV range expected from various magnitude earthquakes at a 2.5 km epicentral distance, reproduced in Figure 3.

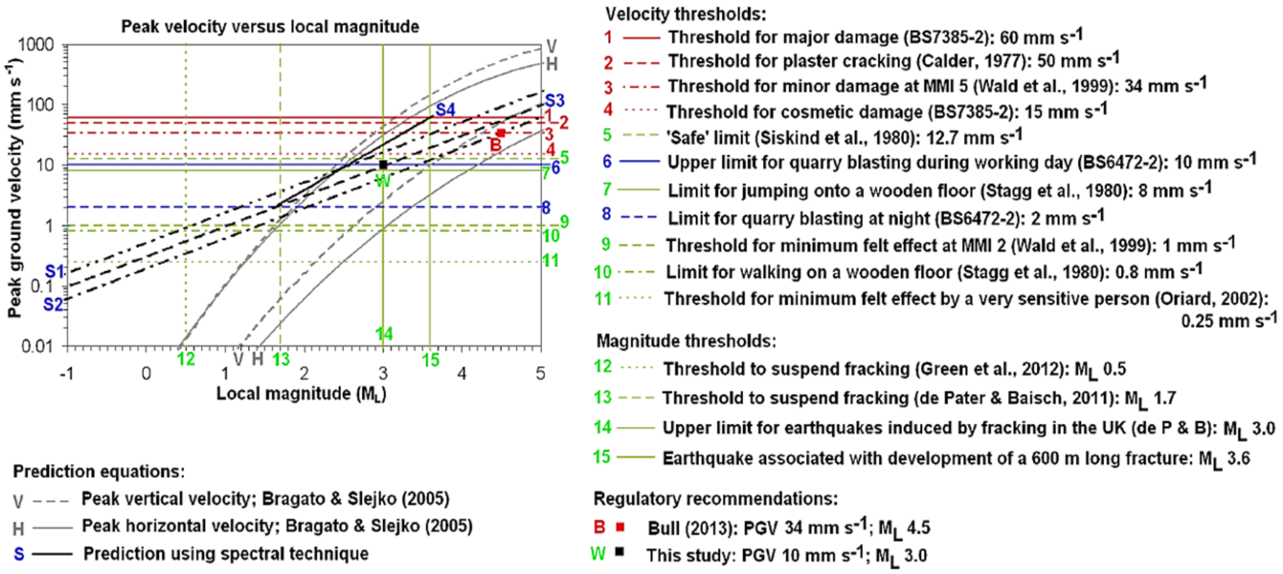


Fig. 3. Estimate of Peak Ground Velocity from Local Magnitude for fracking induced earthquake at epicentral distance of 2.5 km, relative to safe thresholds for ground motion taken from various sources, from Westaway &Younger (2014).

Airborne: Selective scaling and mixing of bands in modern airborne multi-spectral scanners preferentially reinforce combined surface features such as colour tones and high thermal IR associated with wet ground. Cooper (1989) used combined bands to identify water-filled hollows in fine Quaternary soils affected by subsidence in the underlying Triassic in Ripon. Exploiting the high resolution NERC airborne thematic mapper with roughness analysis of images captured under low angle solar radiation, Whitworth et al. (2005) undertook detailed terrain evaluation of the progressive, complex landslides in the Charmouth Mudstone and cambering in the Inferior Oolite in the Cotswolds. Gunn et al. (2008) concluded that detection of unmapped shafts in former mining areas (Yorkshire, Lancashire and Nottinghamshire) using thermal IR depended upon the disruption to near-surface morphological, drainage and vegetation conditions.

Geological Applications

This application mainly relates to mapping geomorphological and subsurface boundaries related to distribution of drift and bedrock, weathering and erosion, structure and discontinuities such as natural faults and joints. *Gravity* contributions include development of microgravity instruments capable of fine resolution (10 microgals) enabling more effective detection of voids within shallow heterogeneous karst. Styles et al. (2005) provide microgravity case histories of karst surveys in the UK and the Bahamas, indicating the depth and geomorphology of shallow void networks. Using dynamic probing, Tuckwell et al. (2008) confirmed weak ground disturbed by void collapse and doline formation in the Chalk (Hertfordshire, UK) that coincided with five negative microgravity anomalies between 40 and 100 microgals.

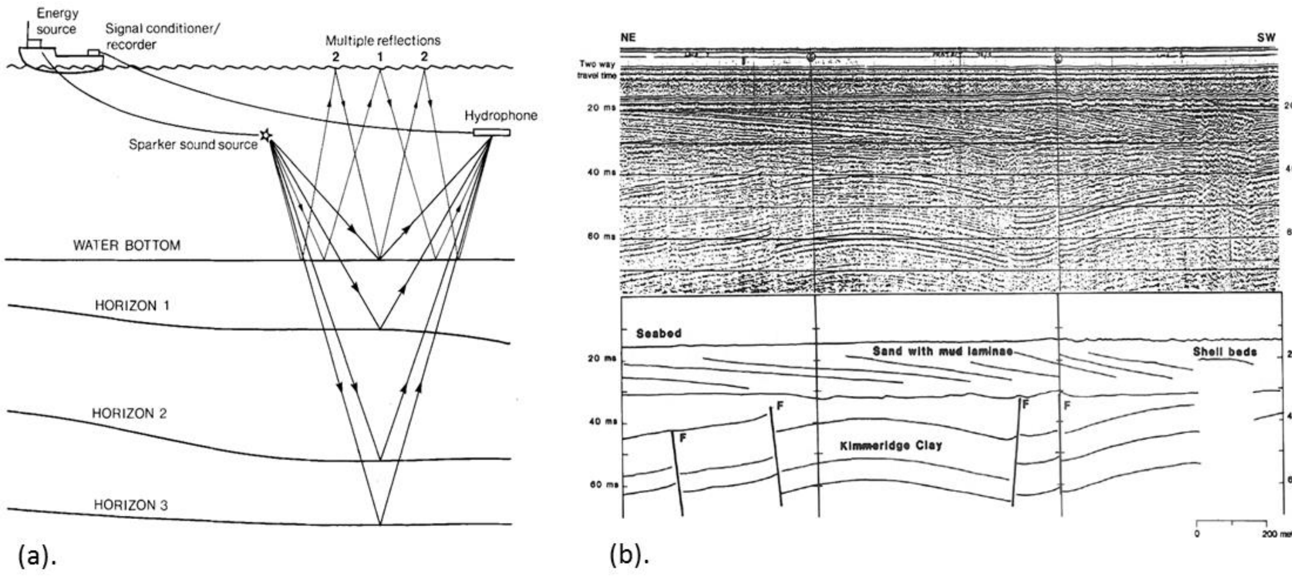
Electrical Resistivity methods are shown to be particularly effective in river catchments, such as multiple 1D soundings by McDowell et al. (1970) to interpret 2D sections of peat, alluvial clays overlying gravel terraces above Jurassic mudstone bedrock in Cambs, interpreted by Homles (1971) to have resulted from multi-channel deposition in ancient river systems. Salvany et al. (2004) used multiple vertical resistivity soundings to develop conceptual model sections of the gravel terraces over marlstones for the design and construction of a barrier to inhibit the flow of the Agrio river into a downstream aquifer. Eleraki et al. (2010) used vertical Schlumberger soundings and 2D Wenner sections to aid the lithofacies differentiation of ephemeral lake deposits in dessert wadi to aid understanding of underground waste water movement within the East Nile delta; where the zone of saturation was important for identifying surface seep locations. Gunn et al. (2013) inferred Whitby Mudstone flow lobes over Staithes Sandstone using a pseudo-3D resistivity model, which also aided classification of the geomorphological features of a complex landslide near Malton, Yorks.

Seismic Refraction methods provide high resolution sections in tidal coastal sedimentary settings such as the use of explosive sources and 120 m P-wave refraction lines by Brabham et al. (1999) to map the thickness of glaciofluvial gravels and glaciolacustrine clays over Ordovician sandstones and siltstones in the Porth Neigwl glacial valley in Llyn, and using close-spaced geophones and overlapping lines, Brabham & MacDonald (1992) mapped a buried channel of tidal sands/gravels in the Carboniferous Limestone of Barry Island.

Seismic Reflection: Morris & Barker (1990) summarised the Joint Association for Geophysics (JAG) meeting, 'Shallow reflection seismic-where are we now?' on techniques to investigate shallow geological structures down to depths of 100 m, which included three basic principles papers by Hill (1992a) on field sources, geophone arrays and recording instruments, King (1992) on the common mid-point survey configuration and resulting field records and the excellent paper by Davies & King (1992) on reflection seismic processing. Much good practice used 24 channel systems and high frequency, explosive sources to produce reflection seismograms for lithostratigraphic interpretation, such as, the Mercia Mudstone overlapping Charnian by Hill (1992b) aiding gypsum mining in Leicestershire, and the mapping of foundation conditions by Nichol & Reynolds (2002) who mapped glaciolacustrine infill over Silurian Flagstones for the A5 bridge replacement at Pont Melin Rug, and Lenham et al. (2005) who mapped the Runcorn Sands (and silts) over Triassic sandstone in the Mersey Esturary. Meeks (1992) obtained long duration seismograms but with high frequency/resolution in the fully saturated fluviatile and coastal sands of Rucphen, Netherlands. Brabham et al. (2005) showed by rolling along daisy-chained systems, long sections can be covered over old lake beds in Shropshire, the Llandrhidian Marshes in Gower and tidal beaches of the St. Bees and Llyn coasts.

Using boat-towed, high voltage sparker sources and shingle channel continuous reflection profiling, superb seismograms were produced by Conway et al. (1984) of estuarine silts and coastal terraces over the London Clay in the Crouch/Roach rivers, Essex, and by Dobinson & McCann (1990) of shallow marine sand/gravel aggregate bars over the Mesozoic in Lyme Bay and the Wash, reproduced in Figure 4.

Fig. 4. Marine continuous reflection profiling based on (a) towed high-voltage sparker source and single channel receiver, from Conway et al. (1984) used to create high resolution marine seismograms, such as (b) interbedded sand and mud laminae over Kimmeridge Clay from the Wash, East Anglia, from Dobinson & McCann (1990).



Borehole: Seismic and Sonic contributions include apparent velocity intervals through Quaternary alluvium/terraces and the Woolwich-Thanet overlying Chalk by Kirkpatrick & McCann (1984), contributing to the ground model used to design the Barking flood barrier. Explosive and sparker sources provided the high frequencies for the innovative cross-hole methods by Goulty et al. (1990) to map seams in the Durham Coal Measures using sub-horizontal seam waves, bent-ray tomography and uphole transformations, to produce a horizontal series of common shot gathers on the hydrophone string in the receiving borehole.

Very recent *Electromagnetic* HiRES 25 kHz airborne surveys included flights reported by Beamish & White (2012) for rapid geological mapping over the Isle of Wight, which via tagging properties to the BGS Rock Classification Scheme, provided a basis for attributing near surface electrical conductivity to southern English litho-stratigraphy. Busby et al. (2011) generated a synthetic resistivity map of the Isle of Wight based upon the populations of ground based surveys held in the UK National Resistivity Sounding Database the resistivity, which showed good agreement with the HiRES survey. Busby et al (2012) integrated this methodology with soil thickness and penetration databases to develop a geo-spatial decision support tool for electrical earthing methods over the Midlands and SE England.

Resource Applications

This relates to naturally occurring minerals for manufacturing and industrial processes, materials for cement and aggregates for construction and building, potable water and associated geo-environmental contamination or blight of these resources. *Borehole Resistivity* methods are effective in aquifer characterisation, and the focused Dual Laterolog was especially effective at overcoming mud-invasion of the borehole wall as used by Brassington et al. (1992) to define saline intrusion within the Collyhurst Sandstone at the base of the NW P-T aquifer. Brassington & Taylor (2012) have continued to monitor the top of the saline zone across the NW P-T aquifer using several boreholes. Borehole logs can be calibrated via integration of core resistivity measurements enabling greater understanding of aquifer properties, such as the investigation of horizontal-vertical formation factor and permeability anisotropy of P-T sandstone core taken from the Fylde district by Barker & Worthington (1973). Worthington (1986) also explored the use of these core properties in a quantitative evaluation of the potential yield of both water and hydrocarbon reservoirs, and Barker (1994) provides further data on the formation factor and hydraulic conductivity of Humberside Chalk core. Also, examples of correlating borehole logs with field resistivity soundings include Hawkins & Chadha (1990) who mapped the P-T aquifer to depths of 200 m identifying several up-thrown blocks along E-W trending faults in the Vale of York. Also, cross-hole resistivity tomography has been used effectively to identify high transmissivity fractures during packer tests by Brown & Slater (1999) in the Carboniferous Limestone (Cumbria) and by Zaidman et al. (1999) during tracer tests to evaluate the influence of factures on drainage in the unsaturated North Downs Chalk, Yorkshire.

Field Resistivity methods can be effective in aggregates, provided that groundwater levels are understood, and MacDonald et al. (1999) provide an example of mapping aquifer subcrop away from local calibration boreholes in Thames gravel terraces, and by applying a simple resistivity-thickness index (simple Dar Zarrouk parameters) to surrounding vertical soundings provided a potential aquifer transmissivity map about the boreholes. Cuthbert et al. (2009) used 2D resistivity images to distinguish fine glaciolacustrine from coarse glaciofluvial cover, which sparked much debate from Shepley & Voyce (2010) regarding the significance of local versus catchment scale heterogeneity on the recharge of the Shropshire P-T aquifer, part reproduced in Figure 5. The resistivity of Quaternary outwash materials is highly dependent upon grainsize mixing and saturation, leading to reports such as by Crimes et al. (1994) of underestimation of sand and gravel thicknesses by 29% using Wenner resistivity soundings when compared to local borehole logs.

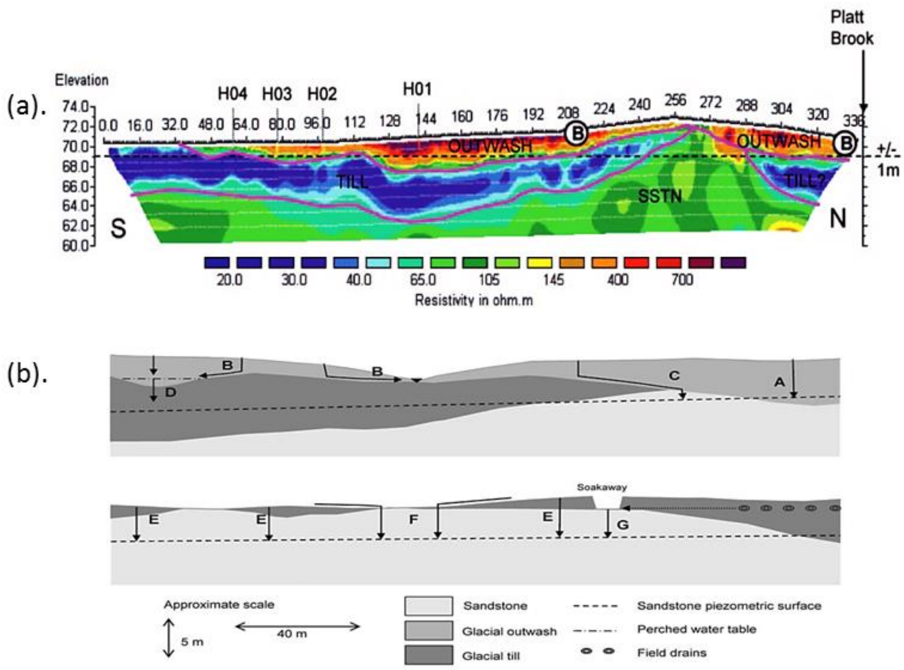


Fig. 5. Use of roll-along Wenner soundings to create (a) 2D apparent electrical resistivity tomograms from which (b) conceptual models for the recharge of the Shropshire P-T aquifer were developed, from Cuthbert et al. 2009.

GPR: contributions are rare, but using single hole 100 MHz GPR profiling, Godio (2014) mapped circumferential borehole fractures, which were integrated with fractures and high transmissivity layers extending from the borehole into clayey calcareous marls mapped using cross-hole GPR tomograms. *Induced Polarisation* contributions include study of clay proportion on chargeability and permeability in cores from the Fylde P-T sandstone aquifer by Collar & Griffiths (1976), and of the control of pore water chemistry and pore morphology on the real and imaginary chargeability components by Scott & Barker (2005). Regarding use of Spon*taneous Potential*, Jackson et al. (2012) reported +ve anomalies associated with aquifer drawdown and –ve anomalies with recovery of the abstraction cones in the Chalk.

Engineering Applications

This relates to ground classification and assessment for civil engineering, including survey of static properties or monitoring of dynamic processes in relation to geotechnical, geochemical, geomechanical or deformation behaviour associated with engineering activities in the subsurface and surface excavation. *Seismic Refraction* contributions include the novel application of spectral P-wave attenuation by Murphy & Rosenbaum (1989) for rock mass assessment of Devonian rocks, and the development of field seismographs with radio telecoms enabled Young et al. (1985a,b) to produce an attenuation-based brokenness index of the shallow Coal Measures used to aid open cast coal dragline excavation planning. Also Hope et al. (1999) used geophone measurements down two adjacent boreholes to overcome continual refraction of shear waves in poorly consolidated clays in Bothkennar, Scotland to produce shear wave velocity-depth profiles, reproduced in Figure 6.

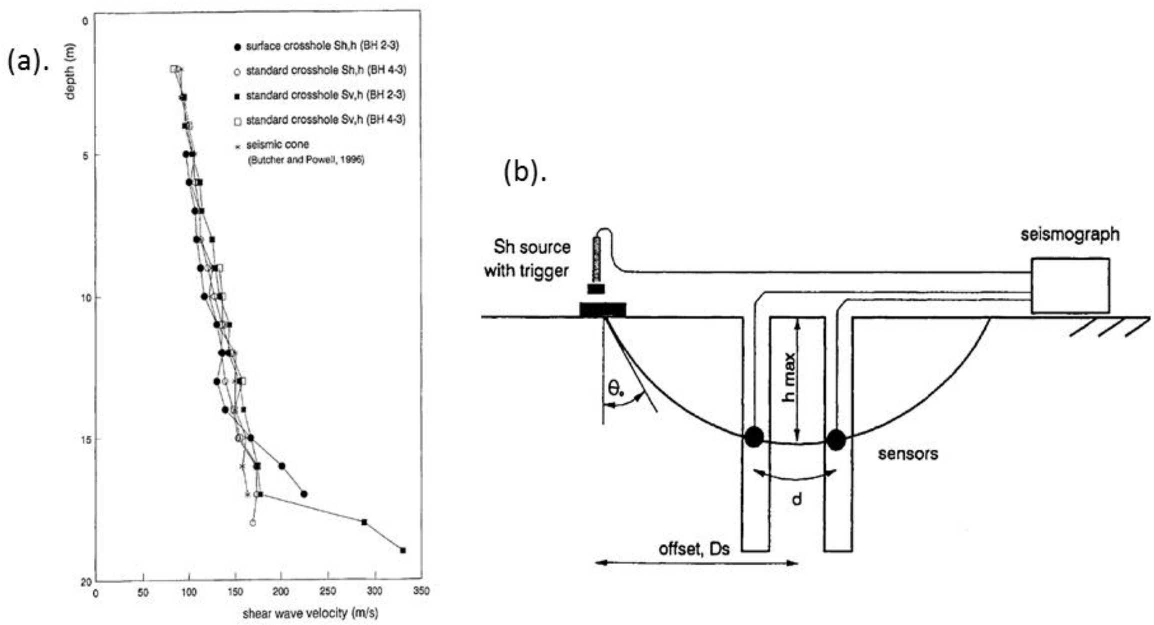


Fig. 6. Field measurement of (a) shear wave velocity-depth profiles involving(b) propagation delay between receivers in two boreholes to overcome continuous refraction, from Hope (1999).

Borehole: Seismic and Sonic contributions include a fracture index based on sonic, neutron and electrical downhole logs for differentiating between open and closed fractures developed by McEwen et al. (1985) for geothermal assessment of Halladale Granite and Moine metasediments. Using gamma tomography and P- and S-wave velocity-porosity relationships from core measurement, Henrikson et al. (1999) investigated the porosity changes due to induration and the effect of fracturing on the elastic moduli of the Danian Limestone in Copenhagen. MacGregor et al. (1994) found a broad positive correlation between rippability productivity of sedimentary rocks in New South Wales and field seismic velocity. Finally, while monitoring hydro-collapse of loessic brickearth under load, in Faversham, Kent, Gunn et al. (2006) used the apparent shear wave velocity between bender element pairs at different depths to investigate the hydrocollapse profile, attributed by Jackson et al. (2006) to rupture of a soil skeletal framework of conductive, inter-particle clay bridges causing increases in *Monitored Resistivity* as opposed to consolidation, which reduced the resistivity.

Infrastructure Applications

This relates to the interface and interactions with the ground that affect or indicate the condition, performance and deterioration of engineered structures and utilities. Geophysical exemplars include many subsurface temperature measurements to investigate heat flow in support of infrastructure for heat harvesting and storage in aquifers.

Building on the 1980s programme, ‘Investigation of the Geothermal Potential of the UK’ , Barker et al. (2000) presented the current understanding of UK heat flow, indicating the hydrothermal potential in some Mesozoic and Palaeozoic basins and Tertiary intrusions. Buss (2009) introduced the ‘Hydrogeology in Heat Engineering’ papers, which began with Banks (2009a) outlining the principles of low enthalpy heat transfer used in ground source heat pumps (GSHP) and reviewing the UK state of the art. Busby et al. (2009) captured the regional heat flow, superficial soil thickness and depth to groundwater in a range of digital products to aid assessment of UK heat transfer potential, reproduced in Figure 7. Banks et al. (2013) have since compiled extensive thermal conductivity data across a range of geology from the Lower Palaeozoic to the Quaternary.

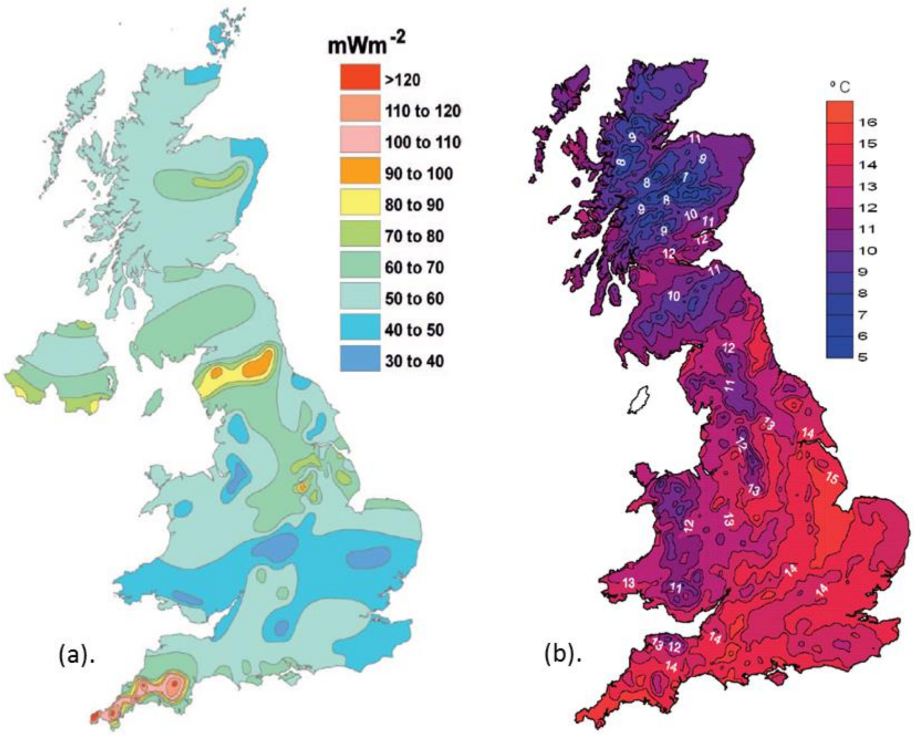


Fig. 7. Investigation of the Geothermal Potential of the UK led to the production of (a) the heat flow map of the UK (measured in $mW.m^{-2}$), which contributes to calculation of (b) shallow subsurface temperature field at 100 m depth, from Busby et al. (2009).

Heat harvesting is prevalent in the South-East, e.g. where Clarkson (2009) describes a high profile open loop system heating the Royal Festival Hall from abstraction and injection wells within the London Lower Tertiaries and Chalk aquifer. Potential contamination arising from heat harvesting has been noted, e.g. by Headon et al. (2009) who attributed higher temperatures on the west side of the Chalk aquifer beneath London to advective flows in the high transmissivity Lower Tertiaries (Woolwich, Reading and Thanet) caused in part by abstraction in East London (River Lea), whereas, Pike et al. (2013) attributed higher temperatures in the Chalk aquifer in Berks and Bucks to greater cover of Tertiary argillites with lower thermal conductivities. Law & MacKay (2010) investigated the effect of fracture flow through the Chalk aquifer on thermal breakthrough in open loop systems, raising questions about the spacing between abstraction and injection wells. Fry (2009) raised the need for regulation to reduce thermal interference between independent London GSHP operations and long term thermal pollution to the Chalk aquifer.

Non-thermal contributions include surface *GPR* profiling using 200 MHz systems by Nichol & Reynolds (1999) to locate wash out voids in the coarse sub-base under the A525 through the Nant-y-Garth Pass and by Nichol et al. (2003) to locate badger burrows in till cuttings near the A55 St. Asaph Bypass. Combined GPR and resistivity imaging were used to evaluate structural integrity by Bishop & Koor (2000) who differentiated between the structural elements and soil fill behind retaining walls in Hong Kong, also confirmed in horizontal drill core. *Magnetic* contributions include mapping of a shallow 0.5 m diameter cast iron pipe buried between 1 to 1.5 m, where the spigot joints were located on a vertical magnetic gradiometer reconnaissance survey by Sowerbutts (1988), from regularly spaced positive gradient concentrations at 6 m.

3. Engineering and Environmental Geophysics for the Future

While describing a future for Engineering and Environmental Geophysics in the Geological Society Engineering Geology SP 12 on Modern Geophysics in Engineering Geology (Eds: McCann et al. 1997), Annan (1997) touched upon broad drivers for development that are still applicable today. Future improvements in the resolution and penetration of the geophysical techniques are likely to be slow in coming, as these are largely controlled by the ground conditions and fundamental physical processes. Fresh, unconventional thinking is required for new approaches, such as Quantum technologies in the GG-Top gravity gradient instruments replacing the old mass on spring gravimeter. Routine technical advances will also bring about more immediate improvements in the sampling, sensitivity, data storage, surveying and processing speed; contributing to the cost effectiveness of geophysical methods. New technologies and methods that can overcome noise and instrumental drift will lead to more power-efficient equipment with improved sensitivity and longer field life. Improvements in surveying and processing speed are in part driven by improved communications, memory and processing power of microprocessor-based instrumentation. While, engineering geophysics receives relatively low investment levels, this is somewhat offset by modern instrumentation developments incorporating high volume, low cost components and fabrication processes.

Other drivers include integration of multiple geophysical methods to invert ground model solutions that incorporate geotechnical property ranges and distributions consistent with all the geophysical datasets. More routine inversion of seismic and electrical tomography for porosity, density and saturation property information is a particular area for development. More routine inversion of geophysical images, especially incorporating time-lapse changes, into *quantified* geotechnical property sections and ground models, would shift the ground engineering paradigm.

Finally, Annan (1997) drew attention to developments arising from industry standards, education, professionalism, conduct and the working relationships between geophysicists and their stakeholders. Fortunately, geophysics is used increasingly by the civil engineering community, especially regarding development of Building Information Models, ground condition monitoring to understand resilience and the impact of extreme stresses, natural and operational changes, and in the development of key indicators of infrastructure performance. The common goals of sustainable engineering solutions provide positive drivers for continued cross-disciplinary strengthening, which has strong support from the UK Research Councils through Living with Environmental Change (LWEC), the Environmental Risk to Infrastructure Innovation Programme(ERIIP) and the nascent UK Collaboratorium for Research in Infrastructure & Cities (UKCRIC). Hence, there are good reasons to be optimistic about the ensuing 50 years.

4. Conclusion

This review provides a backdrop of some events of the times that influenced both the market for geophysical services and their refinement for engineering applications. It demonstrates a significant contribution to geophysics from papers published in the QJEGH (and QJEG) over its fifty years. Subject matter outside of the UK primarily focused upon exploration for resources or seismic hazard assessment, while the UK contributions included a wider range of geophysical methods pertinent to engineering geology and hydrogeology in support of ground assessment, development and construction. The papers returned in this review were classified using the geophysical methods shown in Figure 1, and five application areas: i. Geological Investigation, ii. Resources, iii. Engineering Characterisation, iv. Hazardous Ground and v. Infrastructure. This scheme is a slight extension of the familiar framework used in BS 5930:2015 and is presented in the Appendix as summary tables of the geophysical methods, engineering application, geology and location of all the case studies reviewed. These tables should ease user searches for relevant material and hence encourage access to these papers via the Lyell collection.

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